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FINAL REPORT

EXPERIMENTAL STUDIES OF IONOSPHERIC IRREGULARITIES AND RELATED PLASMA PROCESSES

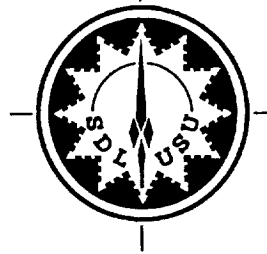
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1. Foreword

The objective of Experimental Studies of Ionospheric Irregularities and Related Plasma Processes (NASA Grant NAG5-603) was to measure and interpret electron density and its variations in a variety of ionospheric conditions from instrumentation onboard sounding rockets. Utah State University (USU) served as Principal Investigator (PI) for rockets in the Thunderstorm II and COPE II campaigns and as Co-Investigator with either Cornell University or University of Alabama at Huntsville on other rockets in various campaigns.

This document is a final report of the activity on this grant. Most of the report consists of the abstracts of papers published and/or presented from this contract when abstracts were available. The total number of publications and presentations connected with this contract is thirty-three.

2. Table of Contents

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3. Overview

Utah State University (USU) continued its program of measuring and interpreting electron density and its variations in a variety of ionospheric conditions with the Experimental Studies of Ionospheric Irregularities and Related Plasma Processes program. The program represented a nearly ten year effort to provide key measurements of electron density and its fluctuations using sounding rockets. The program also involved the joint interpretation of the results in terms of ionospheric processes. See Table 1 on the following page for a complete campaign summary. A brief description of the major rocket campaigns is included below, followed by the titles and abstracts of publications and papers resulting from this work.

3.1 CONDOR Campaign

A series of rockets was launched from Puntalobos, Peru in March 1983 to investigate the equatorial F-region, particularly spread-F, and plasma instabilities in the equatorial electrojet. The CONDOR campaign resulted in excellent data in both the F-region and E-region objectives. Two Taurus Orion vehicles were launched on 9 and 12 March to study electrojet. A high-flying Terrier-Malemute was launched into the F-region 15 March. Instrumentation onboard the rockets included a plasma frequency probe (PFP), electrostatic analyzer (ESA), and dc probe (DCP), as well as instruments provided by Cornell University. The first launch reached an apogee of 125 km, the second 128 km, and the third 535 km.

Electric field and plasma density instrumentation onboard the CONDOR sounding rockets detected intense electrostatic waves indicative of plasma instabilities in the day time equatorial electrojet. Simultaneous measurements taken by the Jicamarca radar showed strong 3-m type 1 electrojet echoes as well as evidence of kilometer scale horizontally propagating waves. The in situ electric field wave spectra displayed three markedly different height regions within the unstable layer: (1) a two stream region on the topside between 103 and 111 km where the electron current was considered to be strongest; (2) a gradient drift between 90 and 106.5 km where the upward-directed, zero order electron density gradient was unstable, and (3) an "interaction" region between 103 and 106.5 km where both of these instabilities were linearly unstable. The unstable altitudes and differentiation showed good agreement with the simultaneous 3-m Jicamarca backscatter radar observations. In the region where the density gradient was unstable, large amplitude waves with large scale sizes (wavelengths of roughly 1-2 km) were observed. These kilometer-scale waves dominated the observed in situ spectrum, despite the fact that the peak in the linear gradient drift growth rate occurred at wavelengths of only a few hundred meters. Comparisons of the measured δE and $\delta n/n$ components of the large scale waves verified the basic process inherent to the gradient drift instability: density enhancements were observed coincident with westward electric fields,

Table 1. List of Campaigns

MEASUREMENT PROGRAM vehicle	LAUNCH DATE, TIME, SITE	APOGEE	SENSORS	REMARKS/ RESULTS
CONDOR (Electrojet) 33.026 Taurus-Orion	9 March, 1983 ---- Puntalobos, Peru	125 km	PFP, ESA, DCP, E-Fields	I n s t r u m e n t s performed well
CONDOR (Electrojet) 33.027 Taurus-Orion	12 March, 1983 1534 GMT Puntalobos, Peru	128 km	PFP, ESA, DCP, E-Fields	Excellent data
CONDOR (F-Region) 29.019 Terrier Malemute	15 March, 1983 0233 GMT Puntalobos, Peru	535 km	PFP, ESA, DCP, E-Fields	Excellent data
Instr. Test 12.039 WT Taurus/Nike/ Tomahawk	1 Sept., 1983 2248 GMT Wallops Island, VA	362 km	Probe Development	Partial success
Instr. Test ---- Taurus/Nike/ Tomahawk	14 Dec., 1983 1951 GMT Wallops Island, VA	704 km	Probe Development	Good Results

MEASUREMENT PROGRAM vehicle	LAUNCH DATE, TIME, SITE	APOGEE	SENSORS	REMARKS/ RESULTS
COPE I 29.023 Terrier Malemute	23 Jan., 1985 0923 UT Sondestrom, Greenland	325 km	PFP, ETP, E-Field	Good data
COPE I 33.044 Taurus Orion	5 March, 1985 2038 UT SE	135 km	PFP, ETP, E-Field	Good data
CRIT I T3-1253/ 35.014UE Black Brant 10/ Terrier Malemute/ Nihka	13 May, 1986 0340 EDT Wallops Island, VA	403 km	Electrical Fields (Cornell), Particle Analyzer (U of AL), Barium Shape Charges (U of AK), PFP 85-1, DCP 85-1	ACS problems, payload not aligned, low seed density, no conclusive results of critical velocity, instrs. successful
COPE II 38.012 Super 3 Taurus/Nike/ Tomahawk	5 March, 1987 0638 Zul Sondestrom, Greenland	475 km	PFP, FTP, Electrical Fields (Cornell), DC MAG, Particle Spectrometer (UAH)	Despin failed, losing Cornell search coil; all other instruments functioned with good data
COPE II 38.010 Super 1 Taurus/Nike/ Tomahawk	31 March, 1987 0447 Zul Sondestrom, Greenland	468 km	PFP, FTP, Electrical Fields (Cornell), DC MAG, Particle Spectrometer (UAH)	Despin failed, losing search coil & boom, FTP non- function; other instruments functioned with good data

MEASUREMENT PROGRAM vehicle	LAUNCH DATE, TIME, SITE	APOGEE	SENSORS	REMARKS/ RESULTS
COPE II 38.011 Super 2 Taurus/Nike/ Tomahawk	31 March, 1987 0447 Zul Sondestrom, Greenland	442 km	PFP, FTP, Electrical Fields (Cornell), DC MAG, Particle Spectrometer (UJAH)	Despin failed; all other functions and instruments performed properly, giving good data Good data
Thunderstorm II 38.007 Taurus/Nike/ Tomahawk	27 July, 1988 0547 UT Wallops Island, VA	452 km	PFP, FTP, Electrical Fields (Cornell), MAG, Particle	
CRIT II 35.019UE Black Brant 10	4 May, 1989 0142 GMT Wallops Island, VA	427.5 km	PFP, DCP, Electric Fields (Cornell), Particle Analyzer (U of AL), Barium Shape Charges (U of AK), Magnetometer (DSR1)	Extraordinary data; plasma density increased an order of magnitude from Barium burst

and density depletions were associated with eastward fields. The amplitudes (10-15 mV/m) of these horizontal waves were strong enough to drive vertical two stream secondary waves. In the region where these waves existed and the electrojet current was strongest, evidence of wave steepening was seen, and the resulting waveforms of the large structures displayed a "flat-topped" nature. In the lower region of the electrojet, the irregularity power occurred over a broad range of wavelengths, estimated to be in the range of tens of meters to kilometers, and fell off rapidly for the shorter wavelengths. Throughout the gradient drift region, shorter scale waves often occurred in bursts which appeared to be controlled by the larger electric field structures.

Both primary and secondary two stream (Farley-Buneman) waves were detected by in situ electric field and plasma density probes in the strongly driven daytime equatorial electrojet over Peru. Simultaneous Jicamarca radar observations showed strong vertical and oblique 3-m type 1 echoes, also indicative of the two stream mechanism. The rocket data showed the two stream region on the topside of the unstable layer to be situated between 103 and 111 km where the electron current was the strongest. This region was characterized by broadband plasma oscillations extending past 1 kHz in the rocket frame. Furthermore, above 106.5 km, where the electron density gradient was stable, a layer of laminar-like, horizontally propagating two stream waves was detected. These waves were strongest near 108 km, the altitude where previous measurements have shown the electrojet current over Peru to be strongest. The peak rocket frame frequency of these waves was 25 Hz, and the observed broadband electric field and plasma density amplitudes were 2 mV/m and 1-2% rms, respectively. The electric field amplitudes were likely attenuated by a spatial filtering effect and may have been several times higher. The data suggest that these waves had phase velocities comparable to the electron drift velocity (≈ 500 m/s) and peak wavelengths (2-3 m) that agree with kinetic theory predictions. Distinct vertically-oriented waves which may have been generated by a mode-coupling process were also observed by the rocket in this region, in agreement with the simultaneous radar observations. Below the laminar two stream layer, in the region of the large scale, gradient drift-driven horizontal electric fields, secondary two stream waves were observed that were driven by localized $\delta E \times B$ plasma drifts. The amplitudes of the horizontally propagating kilometer scale waves were clearly strong enough (10-15 mV/m) to drive vertically-oriented secondary two stream (type 1) waves and were observed by the Jicamarca radar between 103 and 106 km. Below 103 km, secondary two stream waves could not be generated because ψ (the ratio of the ion and electron collision frequencies to their gyro frequencies) becomes large, despite the fact that the observed large scale wave amplitudes remained strong at the lower altitudes. Observations of "flat-topped" waveforms of the large horizontal electric field structures suggest that secondary two stream phase velocities may be saturated because of a limitation of the driving electric fields rather than a process intrinsic to the two stream instability itself.

The Condor campaign studied the equatorial F region and provided good data on the development of spread F as evidenced by data from backscatter radars, scintillation observations, and digital ionosonde measurements. We argue that at least two factors other than the classical gravitational Rayleigh-Taylor plasma instability process must operate to yield the longest-scale horizontal organization of spread F structures. The horizontal scale typical of plume separation distances can be explained by invoking the effect of a shear in the plasma flow, although detailed comparison with theory seems to require shear frequencies a bit higher than observations indicate. On the other hand, the largest-scale organization or modulation of the scattering layer cannot be explained by the shear theory and must be due to local time variations in the ionospheric drift or to gravity wave-induced vertical motions. Using simultaneous rocket and radar data, we were also able to confirm the often quoted hypothesis that rapid overhead height variations in the scattering region of Jicamarca are primarily spatial structures advecting overhead. The detailed rocket-radar comparison verified several other earlier results and speculations, particularly those made in the PLUMEX experiments. Our data included the role of anomalous diffusion in the theory of equatorial spread F and shed light upon the shallow spectral form often observed in the intermediate scale regime.

3.2 COPE I Campaign

As part of the COPE I campaign, two rockets, using Terrier Malemutes as launch vehicles, were successfully launched from the rocket range at Sondre Stromfjord, Greenland on January 23, 1985 and penetrated the morning auroral oval. The rockets reached an apogee of 325 km. Instrumentation onboard the rockets included a PFP, electron temperature probe (ETP), and E-Field instrument. Simultaneous data were also obtained with the nearby incoherent scatter radar and from the Hilat satellite. Several regions of intense quasi-dc electrostatic turbulence were detected with localized dc field variations on the order of 100mV/m. These changes corresponded to shear frequencies in the range of 5 Hz. The regions of strong turbulence were localized and seem to be related to the discrete auroral arcs over which the rocket passed. In addition, these regions were associated with very intense line emissions near 1.84 MHz, and bursts of broad band signals below 600 kHz. Weaker regions of low frequency turbulence were seen poleward of the discrete arcs, but not equatorward of them. These may be regions of irregularities which convect out of the oval into the polar cap.

3.3 COPE II Campaign

COPE II was an international space science campaign of sounding rockets conducted in Greenland the winter of 1987. The primary purpose was to gather knowledge about the solar-earth relationship with respect to the polar ionosphere. The campaign included studies of polar cap turbulence and electrodynamics, auroral zone electrodynamics, polar cap and theta aurora,

neutral atmosphere coupling and polar ionospheric irregularities. Utah State University participated in three of the ten launches, which used the newly developed rocket payload concept, Super (Small University Payload Experiment Rocket). USU had instrumentation on the Super 3, Super 1, and Super 2 rockets.

Super 3 was launched into an auroral breakup from Sonde Stromford, Greenland on March 5, 1987 at 06:38:40 Zulu following a chemical payload launched six minutes earlier. The payload carried an USU PFP and FTP. Cornell and UAH also had experiments on the flight. Despin failed during the flight and caused the loss of the Cornell search coil and DC magnetometer. The other instruments and payload functions performed well.

Super 1 and Super 2 were part of a three rocket salvo launched into an auroral breakup on March 31, 1987. Launch times were 04:47:05 Zulu for Super 1 and 04:47:11 Zulu for Super 2. The two payloads were identical. Both carried a USU PFP and a FTP. They also carried Cornell's electric field experiment and search coil and UAH's particle spectrometer.

As on the previous launch, despin failed on the Super 1 launch. All other instruments and payload functions performed well.

Again, as on Super 1 and Super 3, the despin failed. This caused the loss of the Cornell search coil upon deployment and one of the forward booms approximately two seconds after its deployment. All other payload functions and instruments performed well.

3.4 CRIT I and CRIT II Campaigns

The Critical Velocity Experiment (CRIT) took measurements in space to check the validity of Alfvén's critical ionization hypothesis. CRIT utilized separately deployed release modules to accelerate barium atoms with shaped charges that were detonated upon command when the proper geometry between the chemical modules, a separate daughter payload and the main payload, was achieved. The USU PFP on the main payload measured the electron density associated with the arrival of the ionizing front. For this particular application, optimization of the PFP response time was critical in order to follow the rapid increase of ionization that was predicted to accompany the event.

Measurements inside the high velocity neutral barium beam of the CRIT II showed a factor of six increase in plasma density in a moving ionizing front. This region was co-located with intense electric fields ($\delta E \approx 300 \text{ mV/m}^2$) perpendicular to the local geomagnetic field and field aligned currents all fluctuating at frequencies well under the lower hybrid frequency for barium but above the oxygen cyclotron frequency. It was determined that these structures were moving with the barium stream near the neutral barium velocity. Large

quasi-dc electric and magnetic field fluctuations were also detected. The heart of the ionizing front, a cross beam of nearly 10 mA/m^2 , was estimated from the magnetic field variation. This is three orders of magnitude higher than typical auroral zone currents associated with auroral arcs. This current sheet was co-located with fluxes of soft electrons which saturated the particle detector. An Alfvén wave with a finite electric field component parallel to the geomagnetic field was observed to propagate along the terrestrial field where it was detected by an instrumented sub-payload.

3.5 Thunderstorm II

The objectives of Thunderstorm II were to study the physics of large transient parallel electric fields due to lightning and the role of directly generated whistlers over thunderstorms in causing midlatitude particle precipitation. These objectives required higher altitudes than the earlier studies. As a result, Thunderstorm II used Taurus Nike Tomahawks to reach an apogee of 452 km. The two high flying rockets were launched over a small thunderstorm cell on July 27, 1988. One of the vehicles was oriented parallel to the earth's magnetic field so that the polarization of lightning-related electric and magnetic fields could be unambiguously determined. In addition, an optical detector allowed group velocity measurements of the signals. Transient electric fields associated with each lightning stroke were detected up to 450 km altitude. The most curious feature was a few millisecond downward electric field pulse which had a large component parallel to the earth's magnetic field. This pulse traveled noticeably faster than the associated whistler wave packet which had electric field perpendicular to the terrestrial field. The pulse was thousands of plasma periods in length and considerably exceeded the runaway electric field. Both the penetration of the pulse into the plasma and its very existence argue that the anomalous resistivity must have been generated in the ionospheric plasma which severely limited the parallel current. The situation is very similar to laboratory experiments in which a parallel electric field is applied to a plasma by discharging a capacitor through an external coil. Magnetic field measurements on the rocket show that small current pulse did occur but was much smaller than the classical parallel productivity would indicate. Intense electrostatic waves with $\delta E \parallel B_0$ were also detected above the lower hybrid frequency.

4. List of Publications (Arranged Chronologically)

A. Journal Articles

1. Pfaff, R.F., M.C. Kelley, B.G. Fejer, N.C. Maynard, and K.D. Baker, In-situ measurements of wave electric fields in the equatorial electrojet, *Geophys. Res. Lett.*, 9, 688, 1982.

Abstract: Electric field wave measurements have been performed on two sounding rockets in the equatorial ionosphere. During a daytime flight from Chilca, Peru, intense electrostatic waves were detected on the upward directed electron density gradient. During a nighttime flight from Kwajalein Atoll, similar waves were detected on a downward directed gradient. These results are in agreement with a gradient drift instability explanation of the generation of the waves. The wave amplitudes were as high as 5 mV/m implying perturbation drifts comparable to the driving drift velocities. Power spectra from the turbulent region show a peak at long wavelengths, followed by a nearly flat spectral region before breaking into a power law form with negative index of 3.6 - 3.7 for $\lambda \leq 30$ m. Similarities between the spectra of the two flights suggest that the fundamental processes of the instabilities are the same in the day and nighttime conditions. The rocket data are consistent with radar results presented in a companion paper which show coherent, kilometer scale waves present in the electrojet.

2. Kelley, M.C., R. Pfaff, K.D. Baker, J.C. Ulwick, R.C. Livingston, C.L. Rino, and R.T. Tsunoda, Simultaneous rocket probe and radar measurements of equatorial spread *F* - transitional and short wavelength results, *J. Geophys. Res.*, 87, 1575, 1982.

Abstract: During the PLUMEX I rocket flight from Kwajalein Island, plasma density and electric field fluctuations were measured in situ, simultaneous with ground-based radar backscatter measurements at 0.96-m and 0.36-m wavelengths. The rocket penetrated an extremely turbulent topside region which had associated intense backscatter. As measured by the radar, the backscatter power was decaying with time during and after the flight. The intermediate wavelength (0.1-10 km) in situ electron density measurements are described in a companion paper, while here we report the traditional and short wavelength results ($\lambda < 100$ m). These data include the first in situ equatorial spread *F* measurements of the electric field component of electrostatic fluctuations with wavelengths less than 1 m. At all altitudes above 280 km, a repeatable form for the wave-number spectrum was found for the electron density and electric field fluctuations at wavelengths less than -about 100 m. The density spectrum varies approximately as k^{-5} and the electric field spectrum as k^{-3} . The steepness of the density spectrum corresponds to an absence of steep edges in the density waveform on the scale of 100 m and less. These two spectral forms are shown to be consistent with an explanation involving low frequency waves with finite wave numbers parallel to the magnetic field ($k_{\perp 1}$). Both theory and laboratory experiments show a power law density fluctuation spectrum for gradient-driven drift waves with negative index in the range 4.5-6.0. Since such waves do have finite $k_{\perp 1}$, and since sharp gradients exist in the spread *F* environment, we conclude that at sufficiently high altitudes, drift waves act

on the steep gradients caused by a primary longer wavelength instability to create the observed spectral form. These waves may then create an anomalous diffusion as discussed Huba and Ossakow (1981b). At lower altitudes a shallower spectral index was observed in the tens of meters range, which may be related to a collisional damping regime. This suggests an altitude threshold for the drift waves that is probably related to ion neutral collisions. The power law spectra show no marked change near $k_{\perp}r_i=1$ where r_i is the ion gyro radius. Since low frequency drift waves are linearly stable for $k_{\perp}r_i \geq 1$, it seems that a wave-wave interaction (cascade) operates to deposit energy in a range where waves are linearly damped. There is a slight suggestion of spectral change (smaller negative index) for $k_{\perp}r_e \geq 0.2$ which may be due to excitation of lower hybrid drift wave and which may be related to the observed enhanced backscatter at wavelengths on the order of 1 m. A stability analysis shows that the plasma is near but on the stable side of the marginal stability boundary for the lower-hybrid drift wave in the most intense region of backscatter. In regions devoid of drift waves, evidence is found for an exponential inner scale cut-off at a wavelength of 200 m.

3. Baker, K.D., J.L. LaBelle, R.F. Pfaff, L.C. Howlett, N.B. Rao, J.C. Ulwick and M.C. Kelley, Absolute electron density measurements in the equatorial ionosphere, *J. Atmos. Terr. Phys.*, 47, 781-789, 1985.

Abstract: Accurate measurement of the electron density profile and its variations is crucial to further progress in understanding the physics of the disturbed equatorial ionosphere. To accomplish this, a plasma frequency probe was included in the payload complement of two rockets flown during the CONDOR rocket campaign conducted from Peru in March 1983. In this paper we present density profiles of the disturbed equatorial ionosphere from a night time flight in which spread-*F* conditions were present and from a day time flight during strong electrojet conditions. Results from both flights are in excellent agreement with simultaneous radar data in that regions of highly disturbed plasma coincide with the radar signatures. The spread-*F* rocket penetrated a topside depletion during both the upleg and downleg. The electrojet measurements showed a profile peaking at $1.3 \times 10^5 \text{ cm}^{-3}$ at 106 km, with large fluctuations having amplitudes of roughly 10% seen only on the upward gradient in electron density. This is in agreement with plasma instability theory. We further show that simultaneous measurements by fixed bias langmuir probes, when normalized at a single point to the altitude profile of electron density, are inadequate to correctly parameterize the observed enhancements and depletions.

4. Kelley, M.C., J. LaBelle, E. Kudeki, B.G. Fejer, S.A. Basu, S.U. Basu, K.D. Baker, C. Hanuise, P. Argo, R.F. Woodman, W.E. Swartz, D.T. Farley,

and J.W. Meriwether, Jr., The Condor equatorial spread F campaign: Overview and results of the large scale measurements, *J. of Geophys. Res.*, 91, 5487-5503, 1986.

Abstract: During the Condor campaign, a number of instruments were set up in Peru to support the rocket experiments. In this series of papers, we report on the results of the experiments designed to study the equatorial F region. In this overview, we summarize the main results as well as report upon the macroscopic developments of spread F as evidences by data from backscatter radars, from scintillation observations, and from digital ionosonde measurements. In this latter regard, we argue here that at least two factors other than the classical gravitational Rayleigh-Taylor plasma instability process must operate to yield the longest-scale horizontal organization of spread F structures. The horizontal scale typical of plume separation distances can be explained by invoking the effect of a shear in the plasma flow, although detailed comparison with theory seems to require shear frequencies a bit higher than observations indicate. On the other hand, the largest-scale organization or modulation of the scattering layer cannot be explained by the shear theory and must be due to local time variations in the ionospheric drift or to gravity wave-induced vertical motions. Using simultaneous rocket and radar data, we were also able to confirm the oft quoted hypothesis that rapid overhead height variations in the scattering region of Jicamarca are primarily spatial structures advecting overhead. The detailed rocket-radar comparison verified several other earlier results and speculations, particularly those made in the PLUMEX experiments. In particular, companion papers discuss and extend some of the PLUMEX results to include the role of anomalous diffusion [LaBelle et al., 1986] in the theory of equatorial spread F and to shed light upon the shallow spectral form often observed in the intermediate scale regime [LaBelle and Kelley, 1986].

5. Baker, K.D., How ground-based observations contribute to rocket, balloon and space shuttle experiments: experience from the past and outlook for the future, Proc. 8th Symposium on European Rocket and Balloon Programmes and Related Research, Sunne, Sweden, 17-23 May 1987, ESA SP-270, pp 87-98, August 1987.

Abstract: Ground-based measurements are key to the understanding and conduct of most measurements programs utilizing rocket- or balloon-borne instruments and also with observations from the space shuttle and platforms deployed from the shuttle. The primary roles of the ground station in conjunction with space-based measurements can be generalized: (1) launch decisions (primarily with sounding rockets); (2) place spot measurements in perspective of long term morphology; (3) additional observational data on the phenomena under study; (4) provide ground truth, intercomparisons and calibration; (5) develop and test new

space measurements techniques. The general ground-based observational techniques of importance are (1) radar; (2) lidar; (3) passive optical and radio observations; and (4) magnetometers and other miscellaneous instruments. Examples are given of past and future rocket, balloon and shuttle measurements campaigns and programs where the ground-based observations are a key and integral part of the overall program.

6. Ulwick, J.C., K.D. Baker, and M.C. Kelley, Comparison of simultaneous MST radar and electron density probe measurements in the polar mesosphere, *Proc. 8th Symposium on European Rocket and Balloon Programmes and Related Research*, Sunne, Sweden, 17-23 May 1987, ESA SP-270, pp. 169-174, August 1987.

Abstract: During the Structure and Atmospheric Turbulence Environment (STATE) campaign in June 1983, three small rockets (Super Arcas) containing dc probes to measure electron density irregularities with high spatial resolution were launched at Poker Flat, Alaska. The rockets were launched at three different times when the nearby MST (mesospheric, stratospheric, and tropospheric) radar showed intense regions of backscatter in the mesosphere. The first and third flights (STATE 1 and STATE 3) were perfectly successful, providing high quality electron density measurements; STATE 2 did not produce any useful results. When the electron density measurements are compared with the radar echo power as a function of altitude for STATE 1 and 3, large fluctuations and strong gradients in the electron density profiles are observed in the region of most intense backscatter. The electron density profiles show different characteristics in the peak scattering region with respect to altitude, electron density gradients, and irregularities. Power spectra of the electron density spatial fluctuations were derived from the measured electron densities for the region approximately 65 to 90 km for several height intervals, with the smallest being approximately 100 m. In the region of the most intense backscatter, the spectral power over the entire frequency range increases by almost 3 orders of magnitude for both rocket data sets. For STATE 1 a linear fit to the log-log power spectral plots between 1.0-80 Hz (i.e., spatial scales from about 500 to 5 m) can be approximated by a power law with an index of about $-(5/3)$, as would be expected in an inertial subrange of homogenous, isotropic turbulence. The spectra, moreover, show a continuous steepening of the spectral slope in viscous subrange at frequencies above 100 Hz (approximately 4.5-0.5 m), giving a much higher spectral index. The STATE 3 spectra, on the other hand, show a steeper spectral index near -2.0 in the inertial subrange but steepening at higher frequencies, as do the STATE 1 data. A detailed intercomparison of the probe data is presented, followed by an absolute comparison between the radar and rocket measurements. Reasonable agreement is seen between the observed echo power profile

and the profile calculated using the 3-m electron density fluctuations obtained from the rocket data.

7. Pfaff, R.F., M.C. Kelley, E. Kudeki, B.G. Fejer, and K.D. Baker, Electric fields and plasma density measurements in the strongly-driven daytime equatorial electrojet: 1. The unstable layer and gradient drift waves, *J. of Geophys. Res.*, 92, 13578-13596, 1987.

Abstract: Electric field and plasma density instrumentation onboard a sounding rocket launched from Punta Lobos, Peru, detected intense electrostatic waves indicative of plasma instabilities in the day time equatorial electrojet. Simultaneous measurements taken by the Jicamarca radar showed strong 3-m type 1 electrojet echoes as well as evidence of kilometer scale horizontally propagating waves. The in situ electric field wave spectra displayed three markedly different height regions within the unstable layer: (1) a two stream region on the topside between 103 and 111 km where the electron current was considered to be strongest; (2) a gradient drift between 90 and 106.5 km where the upward directed, zero order electron density gradient was unstable, and (3) an "interaction" region between 103 and 106.5 km where both of these instabilities were linearly unstable. The unstable altitudes and differentiation showed good agreement with the simultaneous 3-m Jicamarca backscatter radar observations. In the region where the density gradient was unstable, large amplitude waves with large scale sizes (wavelengths of roughly 1-2 km) were observed. These kilometer scale waves dominated the observed in situ spectrum despite the fact the peak in the linear gradient drift growth rate occurred at wavelengths of only a few hundred meters. Comparisons of the measured δE and $\delta n/n$ components of the large scale waves verify the basic process inherent to the gradient drift instability: density enhancements were observed coincident with westward electric fields, and density depletions were associated with eastward fields. The amplitudes (10-15 mV/m) of these horizontal waves were strong enough to drive vertical two stream secondary waves. In the region where these waves existed and the electrojet current was strongest, evidence of wave steepening was seen, and the resulting waveforms of the large structures displayed a "flat-topped" nature. In the lower region of the electrojet, the irregularity power occurred over a broad range of wavelengths, estimated to be in the range of tens of meters to kilometers, and fell off rapidly for the shorter wavelengths. Throughout the gradient drift region, shorter scale waves often occurred in bursts which appeared controlled by the larger electric field structures.

8. Pfaff, R.F., M.C. Kelley, E. Kudeki, B.G. Fejer, and K.D. Baker, Electric fields and plasma density measurements in the strongly-driven daytime equatorial electrojet: 2. Two stream waves, *J. of Geophys. Res.*, 92,

13597-13612, 1987.

Abstract: Both primary and secondary two stream (Farley-Buneman) waves have been detected by in situ electric field and plasma density probes in the strongly driven daytime equatorial electrojet over Peru. Simultaneous Jicamarca radar observations showed strong vertical and oblique 3-m type 1 echoes, also indicative of the two stream mechanism. The rocket data show the two stream region on the topside of the unstable layer to be situated between 103 and 111 km where the electron current was the strongest. This region was characterized by broadband plasma oscillations extending past 1 kHz in the rocket frame. Furthermore, above 106.5 km, where the electron density gradient was stable, a layer of laminar-like, horizontally propagating two stream waves was detected. These waves were strongest near 108 km, the altitude where previous measurements have shown the electrojet current over Peru to be strongest. The peak rocket frame frequency of these waves was 25 Hz, and the observed broadband electric field and plasma density amplitudes were 2 mV/m and 1-2% rms, respectively. The electric field amplitudes were likely attenuated by a spatial filtering effect and may have been several times higher. The data suggest that these waves had phase velocities comparable to the electron drift velocity (≈ 500 m/s) and peak wavelengths (2-3 m) that agree with kinetic theory predictions. Distinct vertically oriented waves which may have been generated by a mode coupling process were also observed by the rocket in this region, in agreement with the simultaneous radar observations. Below the laminar two stream layer, in the region of the large scale, gradient drift-driven horizontal electric fields, secondary two stream waves were observed that were driven by localized $\delta E \times B$ plasma drifts. The amplitudes of the horizontally propagating kilometer scale waves were clearly strong enough (10-15 mV/m) to drive vertically-oriented secondary two stream (type 1) waves, as proposed by Sudan et al. [1973] and observed by the Jicamarca radar between 103 and 106 km. Below 103 km, secondary two stream waves could not be generated because ψ (the ratio of the ion and electron collision frequencies to their gyro frequencies) becomes large, despite the fact that the observed large scale wave amplitudes remained strong at the lower altitudes. Observations of "flat-topped" waveforms of the large horizontal electric field structures suggest that secondary two stream phase velocities may be saturated because of a limitation of the driving electric fields rather than a process intrinsic to the two stream instability itself.

9. Ulwick, J.C., K.D. Baker, M.C. Kelley, B.B. Balsley, and W.L. Ecklund, Comparison of simultaneous MST radar and electron density probe measurements during STATE, *J. of Geophys. Res.*, 93, 6989-7000, 1988.

Abstract: During the Structure and Atmospheric Turbulence Environment

(STATE) campaign in June 1983, three small rockets (Super Arcas) containing dc probes to measure electron density irregularities with high spatial resolution were launched at Poker Flat, Alaska. The rockets were launched at three different times when the nearby MST (mesospheric, stratospheric, and tropospheric) radar showed intense regions of backscatter in the mesosphere. The first and third flights (STATE 1 and STATE 3) were perfectly successful, providing high quality electron density measurements; STATE 2 did not produce any useful results. When the electron density measurements are compared with the radar echo power as a function of altitude for STATE 1 and 3, large fluctuations and strong gradients in the electron density profiles are observed in the region of most intense backscatter. The electron density profiles show different characteristics in the peak scattering region with respect to altitude, electron density gradients, and irregularities. Power spectra of the electron density spatial fluctuations were derived from the measured electron densities for the region approximately 65 to 90 km for several height intervals, with the smallest being approximately 100 m. In the region of the most intense backscatter, the spectral power over the entire frequency range increases by almost 3 orders of magnitude for both rocket data sets. For STATE 1 a linear fit to the log-log power spectral plots between 1.0-80 Hz (i.e., spatial scales from about 500 to 5 m) can be approximated by a power law with an index of about $-(5/3)$, as would be expected in an inertial subrange of homogenous, isotropic turbulence. The spectra, moreover, show a continuous steepening of the spectral slope in viscous subrange at frequencies above 100 Hz (approximately 4.5-0.5 m), giving a much higher spectral index. The STATE 3 spectra, on the other hand, show a steeper spectral index near -2.0 in the inertial subrange but steepening at higher frequencies, as do the STATE 1 data. A detailed intercomparison of the probe data is presented, followed by an absolute comparison between the radar and rocket measurements. Reasonable agreement is seen between the observed echo power profile and the profile calculated using the 3-m electron density fluctuations obtained from the rocket data.

10. Jensen, M.D., and L.C. Howlett, Wide frequency range sinewave VCO with a tunable inductor and capacitor, *IEEE Trans. Instr. Meas.*, 38, 876-881, 1988.

Abstract. A voltage-controlled oscillator with sinewave output has been built using a tuneable inductor along with a tuneable capacitor to operate at frequencies ranging from 100 kHz to over 20 Mhz. The method of tuning the inductor by changing the permeability of its ferrite core and the ability of extending the frequency response of the core are discussed. Dynamic characteristics of the VCO are explained with examples of a parallel and series tank implementation.

11. LaBelle, J., R.J. Sica, C. Kletzing, G.D. Earle, M.C. Kelley, D. Lummerzheim, R.B. Torbert, K.D. Baker, and G. Berg, Ionization from soft electron precipitation in the auroral *F* region, *J. of Geophys. Res.*, **94**, 3791-3798, 1989.

Abstract: Rocket-borne instrumentation, launched into the morning sector auroral zone from Sondre Stromfjord, Greenland, detects electron density enhancements correlated with enhancements in the flux of soft (less than 1 keV) downgoing electrons.) These electron density enhancements seem most likely to have been generated by direct production of ionization at *F* region altitudes. Model calculations of the electron impact ionization rate, based on the measured electron spectrum, lend support to this hypothesis.

12. Swenson, C.M., M.C. Kelley, F. Primdahl, and K.D. Baker, CRIT II electric, magnetic, and density measurements within an ionizing neutral stream, *Geophysical Research Letters*, **17**, 2337-2340, 1990.

Abstract: Measurements from rocket-borne sensors inside a high velocity neutral barium beam show a factor of six increase in plasma density in a moving ionizing front. This region was co-located with intense fluctuating electric fields ($\delta E \sim 300$ mV/m) at frequencies well under the lower hybrid frequency for a barium plasma. Large quasi-DC electric and magnetic field fluctuations were also detected with a large component of the current and the electric field parallel to B_0 . An Alfvén wave with a finite electric field component parallel to the geomagnetic field was observed to propagate along B_0 , where it was detected by an instrumented sub-payload.

13. Kelley, M.C., C.M. Swenson, N. Brenning, K. D. Baker, and R. Pfaff, Electric and Magnetic Field Measurements Inside a High-Velocity Neutral Beam Undergoing Ionization, *J. of Geophys. Res.*, **96**, 9703- 9718, 1991.

Abstract: Vector electric field measurements have been made inside two ionizing, high-velocity streams of barium atoms in the Earth's ionosphere. A variety of electrical phenomena were observed across the frequency spectrum and are presented in this paper, which emphasizes the experimental results. Comparisons with a theoretical model for the interactions of the stream with the magnetic field and ionosphere are presented in a companion paper [Brenning et al. 1991]. A most startling result is that a very large quasi-dc electric field was detected anti parallel to the beam velocity. This by itself is not unreasonable since newly ionized barium ions with their large gyro radii are expected to create such a field. But since the beam had roughly a 45° angle with the magnetic field, B_0 , we find a very large (≥ 500 mV/m) component of E parallel to B_0 .

The fluctuating electric fields were also quite large, in fact, of the same order of magnitude as the quasi-dc pulse. The wave energy was found to maximize at frequencies below the barium lower hybrid frequency and included strong signatures of the oxygen cyclotron frequency. Measurements made on a sub payload separated across B_0 by several hundred meters and along B_0 by several kilometers do not show the large pulse, although a variety of wave emissions were seen. In addition, very large amplitude magnetic field fluctuations were detected in both bursts. Although we have no clear explanation, they appear to be real phenomenon and worthy of further study. Finally, we note that even though the critical ionization velocity effect did not go into a discharge mode in this experiment, remarkable electromagnetic effects were seen in the neutral beam-plasma interaction.

14. M.D. Jensen and K.D. Baker, Measuring ionospheric electron density using the Plasma Frequency Probe, *Journal of Spacecraft and Rockets*, 29, 91-95, 1992.

Abstract: During the past decade, the plasma frequency probe (PFP) has evolved into an accurate, proven method of measuring electron density in the ionosphere above about 90 km. The instrument uses an electrically short antenna mounted on a sounding rocket that is immersed in the plasma and notes the frequency where the antenna impedance is large and non reactive. This frequency is closely related to the plasma frequency, which is a direct function of free electron concentrations. The probe uses phase-locked technology to follow changing electron density. Several sections of the plasma frequency probe circuitry are unique, especially the voltage-controlled oscillator that uses both an electronically tuned capacitor and inductor to give the wide tuning range needed for electron density measurements. The results from two recent sounding rocket flights (Thunderstorm II and CRIT II) under vastly different plasma conditions demonstrate the capabilities of the PFP and show the importance of in situ electron density measurements for understanding plasma processes.

15. Swenson, C.M., M.C. Kelley, N. Brenning, R. Torbert, F. Primdahl, and K.D. Baker, CRIT II electric, magnetic, and density observations in and ionizing neutral jet, *Adv. Space Res.*, 12, 65-90, 1992.

Abstract: Measurements inside a high velocity neutral barium beam show a factor of six increase in plasma density in a moving front. This region was co-located with intense electric fields ($\delta E \approx 300 \text{ mV/m}^2$) perpendicular to the local geomagnetic field and field aligned currents all fluctuating at frequencies well under the lower hybrid frequency for barium but above the oxygen cyclotron frequency. It was determined that these

structures were moving with the barium stream near the neutral barium velocity. Large quasi-dc electric and magnetic field fluctuations were also detected. The heart of the front, a cross beam of nearly 10 mA/m^2 , was estimated from the magnetic field variation. This is three orders of magnitude higher than typical auroral zone currents associated with auroral arcs. This current sheet was co-located with fluxes of soft electrons which saturated the particle detector. An Alfvén wave with a finite electric field component parallel to the geomagnetic field was observed to propagate along B_0 where it was detected by an instrument sub-payload.

B. Presentations

16. Baker, K.D., and N.B. Rao, Electron density measurements in the daytime electrojet, paper presented at CONDOR Data Review Meeting, Cornell University, Jul 1983.
17. Baker, K.D., Equatorial F-region electron density measurements, paper presented at CONDOR Data Review Meeting, Cornell University, Jul 1983.
18. Baker, K.D., L.C. Howlett, N.B. Rao, M.C. Kelley, R.F. Pfaff, J. LaBelle, Plasma density measurements in the equatorial ionosphere, paper presented at 7th International Symposium on Equatorial Aeronomy, Hong Kong, 22-29 Mar 1984.
19. LaBelle, J., M.C. Kelley, P.M. Kintner, R.F. Pfaff, C. Siefring, B.G. Fejer, E. Kudeki, S. Basu, S. Basu, K.D. Baker and N.B. Rao, Sounding rocket investigations of equatorial spread-F, paper presented at 7th International Symposium on Equatorial Aeronomy, Hong Kong, 22-29 Mar 1984.
20. Pfaff, R.F, M.C. Kelley, J. LaBelle, C. Siefring, P. Kintner, E. Kudeki, K.D. Baker, and L.C. Howlett, Electric field and plasma density measurements in the daytime equatorial electrojet, paper presented at 7th International Symposium on Equatorial Aeronomy, Hong Kong, 22-29 Mar 1984.
21. Basu, S., S. Basu, M.C. Kelley, R. Pfaff, E. Kudeki, and K.D. Baker, VHF scintillations and large scale waves in the equatorial electrojet, paper presented at 7th International Symposium on Equatorial Aeronomy, Hong Kong, 22-29 Mar 1984.
22. LaBelle, J., M.C. Kelley, C.E. Seyler, P.M. Kintner, K.D. Baker, The spectrum of density irregularities in equatorial spread-F, paper presented at the Spring 1984 Meeting of the American Geophysical Union, Cincinnati, OH, 14-17 May 1984.

Abstract: Sounding rocket observations of the spectra of density fluctuations associated with Equatorial Spread-F indicate an altitude dependence of the spectral shape. To explain the low-altitude results, we have invoked the theory of Sudan [1983], modified for the plasma processes that occur in Spread-F. It is found that this theory predicts the correct amplitude for the density fluctuations, but the spectral shape does not match the observations as well. A modification is proposed which predicts a steeper spectral slope, more in accordance with observations. In both cases, classical perpendicular diffusion determines the saturation's amplitude.

To investigate the difference in spectra observed over two altitude ranges, we have fit to the data a form for the power spectrum taken from Keskinen and Ossakow [1981]. The fitted spectrum, along with the empirically determined growth and dissipation rates, is next used to calculate the energy pumped into the spectrum at longer wavelengths as well as the energy dissipated at shorter wavelengths. It is found that the energy is balanced by classical collisional effects in the low-altitude case, but energy balance in the high-altitude case requires an enhanced dissipation of about 500 times that due to classical diffusion. This enhanced diffusion may arise naturally from a consideration of the excitation of drift wave turbulence at the shorter scale sizes.

23. Baker, K.D., J.C. Ulwick, M.C. Kelley, B.B. Balsley, Comparison of rocket-probe electron density and MST radar polar mesospheric measurements, paper presented at the Fall Meeting of the American Geophysical Union, San Francisco, CA, 7 Dec 1984 (abstract), EOS, Vol. 65, No. 45, p. 1032, 6 Nov 1984.

Abstract: A companion paper presented spectra from rocket-borne measurements of electron density fluctuations. Using the spectra from the STATE 1 rocket, we show that the viscous cut off scales with turbulence strength in exactly the way predicted by theory. We present the integrated $(\Delta N)^2$ power at $3 \text{ m} \pm 20\%$ for each $1/4$ sec. (approximately 100 m) spectrum from the three rocket flights compared to the corresponding MST radar echo signal-to-noise measurements. The $(\Delta N)^2$ power plots are clearly co-located with the origin of the simultaneously measured radar backscatter signals. However, the rocket data shows much more structure variations within the radar measured turbulent layer, although in one case, STATE 3, the radar results show small scale variations which co-align very well with the large scale variations in the $(\Delta N)^2$ power. When compared to the electron density profiles we find, particularly in the STATE 1 data, that these increases in $(\Delta N)^2$ power co-locate with decreases in electron density. With respect to the origin for the turbulence, we have found evidence in the STATE 1 data

set for an outer scale with a vertical wave number of about 800 m. The turbulence strength seems to be organized by this large wavelength structure which suggests that the microscale waves are controlled by the properties of the larger structures. The latter may be driven by one of the several mechanisms which have been suggested by researchers. We anticipate that a more detailed study of these data will shed light upon the source for summer mesospheric turbulence.

24. Ulwick, J.C., K.D. Baker, M.C. Kelley, Electron density irregularities of the polar mesosphere - STATE Campaign, paper presented at the Fall Meeting of the American Geophysical Union, San Francisco, CA, 7 Dec 1984 (abstract), EOS, Vol. 65, No. 45, p. 1032, 6 Nov 1984.

Abstract: During the STATE campaign, three rockets were launched at Poker Flat, Alaska containing dc (Langmuir-type) probes to measure electron density irregularities with high spatial resolution. The rockets were launched at times when the MST radar showed intense regions of backscatter in the mesosphere. In each case, when the electron density measurements are compared to the radar echo power as a function of altitude, large changes and strong gradients in the electron density are observed in the region of most intense backscatter. However, the electron density profiles show markedly different characteristics, particularly the STATE 3 peak scattering region, where a 'bite out' in the electron density profile of over 50% is observed between 85 and 86 km. From the measurements, spectra of the spatial density fluctuations were derived from approximately 65 to 90 km for several height intervals, with the smallest approximately 100 meters. In general, a fit to the power spectra between 1.0 and 80 Hz (approximately 500 to 5 meters) gives an index of about $-5/3$ as expected in an inertial subrange of homogeneous, isotropic turbulence. In the region of most intense backscatter, however, the power is up over the whole frequency range by almost 3 orders of magnitude. In addition, these spectra show a continuous steepening in the viscous subrange beyond 10^2 Hz (approximately 4.5 m to 0.5 m), giving a much higher spectral index. The electron density profiles and the power spectra from the three rocket flights are compared and discussed. Detailed utilization of these data to compare with the radar measurements for understanding of mesospheric turbulence are contained in a companion paper.

25. Pfaff, R.F., M.C. Kelley, E. Kudeki, and K.D. Baker, In-situ observations of two-stream waves in the equatorial electrojet and their modulation by large scale waves, paper presented at the Spring Meeting of the American Geophysical Union, Baltimore, MD, 28 May 1985 (abstract), EOS, Vol. 66, No. 18, p. 327, 30 Apr 1985.

Abstract: An intense layer of quasi-laminar two-stream waves was

detected at 107 km by in situ electric field and plasma density detectors on a rocket launched from Punta Lobos, Peru, on March 12, 1983, into the highly disturbed daytime electrojet. The waves existed where the gradient in the electron number density was stable for growth, and hence, their spectrum is interpreted as representing that of the "pure" two-stream instability. The strongest waves were polarized in the East-West direction, had wavelengths which corresponded to roughly 2-3 meters and phase velocities which were estimated by several techniques to be approximately 480-500 m/s. The velocity agrees with $E \times B / (1 + \psi)$ and suggests that the primary two stream phase velocities were not saturated at the acoustic velocity (roughly 380 m/s). Below the region of the laminar two stream waves, where the gradient drift process, large amplitude kilometer scale waves were observed. At the top of this region, where the electron current was strong, the large scale waves appeared to modulate the polarization electric field, as indicated by the "control" of the short scale waves by the large scale wave fields. Specifically, the short scale waves were diminished in the presence of a westward large scale wave and were enhanced where the phase of the large scale wave was eastward. The measured horizontal electric fields of the kilometer scale waves were 10-15 mV/m -- strong enough to drive secondary two stream waves via a two step mechanism, but not larger than those required to satisfy $\delta E / B - C_s (1 + \psi)$. Furthermore, in some cases, the existence of a "flat topped" signature in the large scale waveforms suggests that the secondary two stream phase velocities were saturated due to a limitation of the driving electric fields rather than due to a process intrinsic to the two stream mechanism itself.

26. M.C. Kelley, G.D. Earle, J.F. Vickery, R.B. Torbert, and L.C. Howlett, Preliminary results from the COPE rocket campaign, paper presented at the Spring Meeting of the American Geophysical Union, Baltimore, MD, 28 May 1985 (abstract), EOS, Vol. 66, No. 18, p. 346, 30 Apr 1985.

Abstract: Two rockets were successfully launched from the rocket range at Sondre Stromfjord, Greenland on January 23, 1985 and penetrated the morning auroral oval. Simultaneous data were also obtained with the nearby incoherent scatter radar and from the Hikat satellite. In this paper, we present results from one of these rockets and briefly relate them to the radar and satellite data. Several regions of intense quasi-dc electrostatic turbulence were detected with localized dc field variations on the order of 100mV/m. These changes corresponded to shear frequencies in the range of 5 Hz. The regions of strong turbulence were localized and seem to be related to the discrete auroral arcs over which the rocket passed. In addition, these regions were associated with very intense line emissions near 1.84 MHz, and bursts of broad band signals below 600 kHz. Weaker regions of low frequency turbulence were seen poleward of the discrete arcs, but not equatorward of them. These may be regions of irregularities

which convect out of the oval into the polar cap.

27. Ulwick, J.C., K.D., Baker, and M.C. Kelley, Comparison of simultaneous MST radar and electron density probe measurements in the polar mesosphere, 8th Symposium on European Rocket and Balloon Programmes and Related Research, Sunne Sweden, 17 - 23 May 1987, published in ESA Symposium Proceedings, 1987.

Abstract: During the Structure and Atmospheric Turbulence Environment (STATE) campaign in June 1983, three small rockets (Super Arcas) containing dc probes to measure electron density irregularities with high spatial resolution were launched at Poker Flat, Alaska. The rockets were launched at three different times when the nearby MST (mesospheric, stratospheric, and tropospheric) radar showed intense regions of backscatter in the mesosphere. The first and third flights (STATE 1 and STATE 3) were perfectly successful, providing high quality electron density measurements; STATE 2 did not produce any useful results. When the electron density measurements are compared with the radar echo power as a function of altitude for STATE 1 and 3, large fluctuations and strong gradients in the electron density profiles are observed in the region of most intense backscatter. The electron density profiles show different characteristics in the peak scattering region with respect to altitude, electron density gradients, and irregularities. Power spectra of the electron density spatial fluctuations were derived from the measured electron densities for the region approximately 65 to 90 km for several height intervals, with the smallest being approximately 100 m. In the region of the most intense backscatter, the spectral power over the entire frequency range increases by almost 3 orders of magnitude for both rocket data sets. For STATE 1 a linear fit to the log-log power spectral plots between 1.0-80 Hz (i.e., spatial scales from about 500 to 5 m) can be approximated by a power law with an index of about $-(5/3)$, as would be expected in an inertial subrange of homogenous, isotropic turbulence. The spectra, moreover, show a continuous steepening of the spectral slope in viscous subrange at frequencies above 100 Hz (approximately 4.5-0.5 m), giving a much higher spectral index. The STATE 3 spectra, on the other hand, show a steeper spectral index near -2.0 in the inertial subrange but steepening at higher frequencies, as do the STATE 1 data. A detailed intercomparison of the probe data is presented, followed by an absolute comparison between the radar and rocket measurements. Reasonable agreement is seen between the observed echo power profile and the profile calculated using the 3-m electron density fluctuations obtained from the rocket data.

28. Kelley, M.C., J.Q. Ding, G. Berg, R.H. Holzworth, K.D. Baker, R.B. Torbert, Lightning effects in the ionosphere above 400 km: the Thunderstorm II Campaign, paper presented at the AGU Fall Meeting, San Francisco, Dec

1988.

Abstract: Two sounding rockets were launched simultaneously from Wallops Island, VA in July 1988 over a thunderstorm. The payloads included energetic particle flux (up to 30 keV), density and temperature, optical lightning transient and electric field instrumentation in order to investigate the plasma environment of the ionosphere during lightning events. This paper will present an overview of the early results which include the detection of electric fields with amplitudes over 50 mV/m measured above the F2 peak in the ionosphere. Many events were recorded simultaneously by both rocket payloads at horizontal distances greater than 50 km from the thunderstorm. The total number of lightning strokes detected both optically and electrically is well over 100 during the 10 minute flights.

29. Kelley, M.C., J. Ding, K.D. Baker, R.H. Holzworth, Lightning related electric fields in the ionosphere, paper presented at the 1989 Fall AGU Meeting, San Francisco, Dec, 1989. (abstract) EOS Vol 70, No 43, 24 Oct 1989.

Abstract: Two high flying rockets were launched over a small thunderstorm cell on July 27, 1988. One of the vehicles was oriented parallel to the earth's magnetic field so that the polarization of lightning-related electric and magnetic fields could be unambiguously determined. In addition, an optical detector allowed group velocity measurements of the signals. Transient electric fields associated with each lightning stroke were detected up to 450 km altitude. The most curious feature was a few millisecond downward electric field pulse which had a large component parallel to the earth's magnetic field. This pulse traveled noticeably faster than the associated whistler wave packet which had electric field perpendicular to B_0 . The pulse was thousands of plasma periods in length and considerably exceeded the runaway electric field. Both the penetration of the pulse into the plasma and its very existence argue that the anomalous resistivity must have been generated in the ionospheric plasma which severely limited the parallel current. The situation is very similar to laboratory experiments in which a parallel electric field is applied to a plasma by discharging a capacitor through an external coil. Magnetic field measurements on the rocket show that small current pulse did occur but was much smaller than the classical parallel productivity would indicate. Intense electrostatic waves with $\delta E \parallel B_0$ were also detected above the lower hybrid frequency.

30. Swenson, C.M., M.C. Kelley, F. Primdahl, K.D. Baker, N. Brenning, R.B. Torbert, Electric, magnetic, and density observations in an ionizing neutral jet, paper presented at the 1989 Fall AGU Meeting, San Francisco. (abstract) EOS Vol 70, No 43, 24 Oct 1989.

Abstract: In the CRIT II experiment, we have detected very large amplitude low frequency electric field fluctuations (several hundred mV/m) accompanying the very fastest neutral atoms. The associated ions were measured at low energies, indicating that a rapid process was acting both to form the ions and to scatter them to lower energy. The same ionized region exhibited quasi-DC electric (150 mV/m) and magnetic field (300 nT) pulses as well as magnetic field fluctuations of 60 nT. Furthermore, the plasma density increased by nearly an order of magnitude relative to the background. An electromagnetic pulse was seen to propagate up the field line to a sub payload.

31. Swenson, C.M., M.C. Kelley, F. Primdahl, K.D. Baker, N. Brenning and R. Torbert, Electric, magnetic and density observations in an ionizing neutral jet, Twenty-eighth plenary meeting of COSPAR, The Hague, The Netherlands, 25 June - 6 July 1990.

Abstract: In the CRIT II experiment we have detected very large amplitude (several hundred mV/m) low frequency (500 Hz to 1500 Hz) electric field fluctuations accompanying the very fastest neutral atoms. These electric field fluctuations are observed to be nearly circular polarized and aligned with the neutral stream. The associated ions were measured at low energies indicating that a rapid process was acting both to form the ions and to scatter them to lower energy. The same ionized region exhibited quasi-DC electrical and magnetic field pulses that repeat with the newly created ions' cyclotron period. Furthermore, the plasma density increased by nearly an order of magnitude relative to the background. Magnetic and electric field pulses were seen to propagate up the field line from the ionization region to a sub payload.

32. Swenson, Charles M., The critical velocity effect and recent space experiments, paper presented at Spring Meeting of the Utah Academy of Sciences, Arts and Letters, Salt Lake City, May 1992.

Abstract: Proposed in the early 40's by Hannes Alfvén, the only recipient of a Nobel Prize in the field of plasma physics, the critical velocity effect (CIV) may play a major role in the formation, shaping, and distribution of matter in the universe. It is a mechanism whereby the kinetic energy of a neutral cloud relative to a magnetized plasma is used for self-ionization of the neutral cloud. The magnetized plasma through which the neutral cloud passes acts as a type of catalyst, promoting a reaction that would not otherwise occur. For the past 30 years, the question of whether a magnetized plasma can act as such a catalyst for the ionization of a streaming gas has been studied in the laboratory where the basic concept has been proven correct. In this paper, we report on CIV and on a set of rocket-borne experiment, CRIT I and II, which were conducted in the

Earth's ionosphere. These tests of the critical ionization velocity effect, carried out in space where CIV was originally proposed to occur, have shed new light on this fundamental question.

33. Jensen, Mark D., Adapting the Plasma Frequency Probe to Satellite Platforms, paper presented at Spring Meeting of the Utah Academy of Sciences, Arts and Letters, Salt Lake City, May 1992.

Abstract: The Plasma Frequency Probe (PFP) was developed by Utah State University to make absolute electron density measurements in the ionosphere onboard sounding rockets. Numerous flights over the past 20 years have proven the instrument capable and reliable in determining electron density in many different types of ionospheric conditions. The recent Spread-F Campaign (August, 1990) from Kwajalein Atoll in the South Pacific is another example of how the PFP can accurately describe a turbulent ionosphere. The PFP is now being considered a part of the 77 satellite IRIDIUM (Motorola) constellation. When onboard, the PFP would provide real time global measurements of electron density and ionospheric fluctuations. Efforts are now under way to adapt the PFP to the IRIDIUM satellite platform.

APPENDIX A: GRADUATE STUDENT RESEARCH

The following students received support and completed their Master's degrees while working on this contract:

Glen Berg, Master of Science, Physics, 1989

Title: *Measurements and Analysis of Plasma Density Irregularities in the Auroral Ionosphere*

Abstract: Two rockets were launched from Sondre Stromfjord, Greenland in January and March of 1985 carrying a Utah State University plasma frequency probe (PFP) to measure electron density. The January probe, denoted with the high flier, measured electron densities from 95 to 330 km altitude with a peak F layer density of $2.1 \times 10^5 \text{ cm}^{-3}$ at 235 km on ascent and $1.2 \times 10^5 \text{ cm}^{-3}$ on descent. The March probe, denoted the low flier, measured electron densities from 105 to 135 km with a peak E layer density of $4 \times 10^4 \text{ cm}^{-3}$ at 108 km on ascent and $6 \times 10^4 \text{ cm}^{-3}$ at 132 km on descent.

The contrasting upleg and downleg density profiles on each flight, combined with the shape of each individual profile, suggest the presence of significant horizontal electron density gradients, with scale sizes ranging from tens to hundreds of kilometers. Density enhancements, occurring at 290 km on both the ascent and descent of the high flier, also suggest the presence of significant vertical structure. An on-board energetic electron detector measured a marked increase in soft electron precipitation coincident with both enhancements. The high flier PFP also measured regions of sudden density depletion ("bubbles") between 300 and 330 km, possibly associated with ExB instability.

Power spectral density analysis (PSDA) was used to study electron density waves and turbulence for scale sizes ranging from tens of kilometers to several meters. Various windowing and detrending techniques were explored to reduce spectral leakage, and the Hamming window and high-pass Butterworth filters were chosen for this analysis. Methods for determining wavelength spectra from frequency spectra were also investigated.

Intense electrostatic waves with wavelengths of tens of meters were detected in the E region on both flights. Rms fluctuations about the mean as high as 11% were measured by the low flier PFP. An almost identical electric field spectrum at the same time lends credibility to the measurement. An extremely coherent feature, possibly a two-stream wave, was detected between 100 and 110 km on the high flier upleg at 10.8 Hz, corresponding to a probably wavelength of between 20 or 30 m. Broadband structures ("plateau's") were also measured in the E region on

both flights, as in previous measurements. Analysis of the density gradients and electric field directions suggests that these may be related to the gradient drift instability.

Navin Rao Bondili, Master of Science, Electrical Engineering, 1985

Title: *Power Spectral Analysis of Equatorial Spread-F Electron Density Data*

Abstract: The main objectives of this research were to develop data analysis techniques and analyze electron density irregularity distributions crucial to the study of the instability region unique to earth's equatorial ionosphere, the F-region equatorial spread F (ESF). The electron density results were obtained with the USU plasma frequency probe (PFP) flown on board the Terrier-Malemute, 29.019 sounding rocket launched during March 1983 from Lima, Peru in the equatorial measurements campaign, project CONDOR. The electron density data were derived from two different electronic frequency readouts from the PFP, an analog channel (2020 samples/sec) and a digital channel (62 samples/sec). The digital channel is the most accurate for absolute electron density values and the analog channel provides higher spatial resolution. The electron density profiles showed two distinct electron depletion regions (about 50%) or "bubbles" and were encountered at altitudes of 415 km (upleg) and 455 km (downleg).

The data of the two channels were contaminated once per second due to the resetting of the voltage controlled oscillator (VCO) present in the phase-lock loop (PLL) of the PFP. These contaminated data have to be eliminated to avoid perturbing the spectral analysis of the electron density fluctuations. A spline interpolation technique was used for smoothing over the gaps of data contaminated during the reset pulses. This worked well only on the digital channel data. For analog channel, we employed a neighborhood averaging technique for smoothing. To perform spectral analysis on the smoothed density data for analyzing the short wavelength (< 1 km) and long wavelength (> 1 km) waves, we employed a fast Fourier transform (FFT) routine. The resulting amplitude distributions of the irregularity spectra could be roughly described by a power law of the form k^n , where k is the wave number and n is the spectral index or slope. The spectra showed slopes from -1.0 to -2.5 ± 0.3 (wavelength region 20m-5km).

Laboratory tests on the PFP showed that the minimum meaningful variation of frequency and electron density that could be measured was 7.5 kHz and $1.5 \times 10^3/\text{cm}^3$ respectively. This variation in density value implies about 1% of the daytime E-region maximum density or something down to about 0.1% in the vicinity of the F-region maximum density. Also the instrument noise spectrum was obtained at 8.000 MHz resonating

frequency and exhibited a power spectral density (PSD) less than -90dB/Hz beyond 250 Hz.

Mark Jensen, Master of Science, Electrical Engineering, 1988

Title: *Investigation of Accuracy Limitations of the Ionospheric Plasma Frequency Probe and Recommendations for a New Instrument*

Abstract: A unique wide-range voltage-controlled oscillator (VCO) has been part of the plasma frequency probe (PFP) for many years. The uniqueness of this VCO is how it is tuned with an electronic tuneable inductor in conjunction with a varactor diode. Though the PFP has been utilized successfully for rocketborne ionospheric electron density measurements, fine resolution data was limited by strange frequency jumps (approximately 5 percent uncertainty in electron density) which have appeared in flight results. This thesis examines the cause of some of these jumps, and shows they are instrument related and more particularly caused by the ferrite tank inductor core of the VCO. Investigation was also centered on improving the performance of the VCO, enabling it to respond to faster changes of electron density in the ionosphere. As a consequence of this investigation, methods of extending the maximum operating frequency of the ferrite tank inductor were found which make possible the use of high permeability ferrites in the VCO. By incorporating a new VCO free from frequency jumps with better linearity and speed along with improvements to RF circuitry, results show a new PFP with performance that is markedly improved with respect to accuracy, speed, and reliability.

Charles Swenson, Master of Science, Electrical Engineering, 1989

Title: *An Evaluation of the Plasma Frequency Probe*

Abstract: Electron density in a plasma can be measured by determining the plasma frequency. For 20 years this electron density measurement technique has been used with the plasma frequency probe. The purpose of this paper is to characterize, evaluate, and suggest improvements for this instrument. Although the current plasma frequency probe is a highly successful instrument for measuring absolute electron density in the ionosphere, several areas for improvement were found. These were in the radio frequency head and the voltage controlled oscillator. Currently, the plasma frequency probe is approximately 20% accurate in determining absolute densities around 1.5×10^4 electrons/cm³ but better than 5% accurate at densities greater than 1.5×10^5 electrons/cm³. The errors result from systematic instrument error that can be improved. A model for the plasma frequency probe is developed to help explain the dynamics of the instrument. The use of this model in choosing instrument

components should solve the problems of frequency aliasing with the present instrument. Attempts to band limit the instrument above 700 hz have failed, resulting in a low slew rate, unexplainable by system modeling, dominating the system. Further analysis is suggested in several areas, including slew rate.

Ray-Harng Siao also performed research under this grant.

Both Glen Berg and Charles Swenson completed their M.S. degrees at USU and then continued their work on data partially gathered under the USU/NASA at Cornell University in Ph.D. programs. Glen Berg's dissertation title is *Polar Cap Auroral Arcs: Observations, Theories and a Numerical Model*. He expects to complete his work by early 1993. Charles Swenson's dissertation title and abstract is below.

Charles Swenson, PhD, Electrical Engineering, Cornell University, 1991

Title: *In Situ Observations of an Ionospheric Critical Velocity Experiment*

Abstract: The critical ionization velocity effect (CIV), proposed by Hannes

Alfvén, may play a major role in the formation, shaping, and distribution of matter in the universe. It is a mechanism whereby the kinetic energy of a neutral cloud relative to a magnetized plasma is used for self-ionization of the neutral cloud. The magnetized plasma through which the neutral cloud passes acts as a type of catalyst, promoting a reaction that would not otherwise occur. For the past 30 years the question of whether a magnetized plasma can act as such a catalyst for the ionization of a streaming gas has been studied in the laboratory where the basic concept has been proven correct. In this thesis we report on a set of rocket borne CIV experiments, CRIT I & II, which were conducted in the ionosphere with barium.

We present measurements of the plasma density, electric fields, magnetic fields, energetic electrons, and energetic ions within the ionizing barium stream. Plasma density enhancements were observed and are shown to be signatures of a CIV process albeit one which is less efficient than theory suggests. Other signatures of CIV such as scattering and slowing of the newly created barium ions, heating of the electrons, and the emission of an Alfvén waves from the ionization regions were also detected.

We have found that waves within the region where CIV is active are not the classical lower hybrid waves as predicted by current theories. Since waves of some sort are required by all conceivable theories linking the

beam energy to the electron gas, this result is quite important. Instead we find a low-frequency long-wavelength mode that is in resonance with the barium ion beam ($\omega \approx \kappa \cdot v_{\text{beam}}$). Through an interferometric analysis of the electric field data we show that the wave vector κ of these waves is aligned with the barium beam (57° to B_0) while the electric field of the waves is almost perpendicular to B_0 . Therefore, the wave appears to be a mixed electrostatic and electromagnetic mode. We present a theory for the electrostatic component which appears to dominate the wave characteristics.